HIGH PERFORMANCE CONCRETE STRUCTURES: A WORK IN PROGRESS

Submission Date: July 31, 2002
Word Count: 5,641

William R. Cox, P.E.

Director, Field Operations Section

Bridge Division

Texas Department of Transportation

125 E. 11th Street

Austin, TX 78701

Phone: (512) 416-2189

Fax: (512) 416-2402

wrcox@dot.state.tx.us

Kevin R. Pruski, P.E.

Bridge Field Engineer

Bridge Division

Texas Department of Transportation

125 E. 11th Street

Austin, TX 78701

Phone: (512) 416-2306

Fax: (512) 416-2402

kpruski@dot.state.tx.us

ABSTRACT

Success constructing durable concrete bridges depends on several parameters. Proper design and detailing go part of the way to success, but even the best design is affected by the fact that for state transportation contracts the lowest bidder gets the work. For that reason, crafting precise specifications to instruct contractors, educating the bridge design and construction community on new technologies, and vigorously enforcing contract plans during construction are the keys to obtaining structures that will be around for a long time.

This paper presents the experience of the Texas Department of Transportation (TxDOT) specifying the use of High Performance Concrete (HPC) for bridges, and it provides commentary on how early uses of HPC focused on strength, obtaining the added benefit of improved durability. However, now that concrete strengths normally suited for the majority of bridge structures can be routinely provided by the contracting community, the exciting part of the HPC definition is determining how to get more durable concrete. TxDOT specifications for HPC were initially performance-based, leaving the contractor with options for how to provide the end product. Currently, the specifications that accompany contracts with special emphasis on durability are mostly prescriptive. TxDOT believes that when contractors are aware of project requirements, there is less uncertainty, resulting in better prices and fewer project delays.

INTRODUCTION

The Texas Department of Transportation (TxDOT) has a significant responsibility to construct, operate, and maintain the 79,297 centerline miles of highways and the 32,534 bridges on the state system (as of 2002). TxDOT is a centralized organization that supports 25 districts aligned in unique geographic regions of the state. These geographic regions vary significantly, and the climate where these highways and bridges reside poses different conditions that engineers and planners must address. In general, the state has a climate conducive for long-lasting concrete structures. However, in some regions weather-related events, environmental conditions, and geological conditions can affect the life of a structure, and deterioration of some concrete structures occurs in these locations at a more rapid rate than is acceptable. Most of the distress can be attributed to reinforcing steel corrosion caused by chlorides and moisture penetrating the concrete to a depth of the steel. In the past ten years, despite the measures requiring use of non-reactive aggregates, some significant occurrences of alkali-silica aggregate reactivity (ASR) have resulted in distress in several concrete structures. TxDOT has known since the 1960’s that sulfates in the soil and groundwater were attacking the concrete, and it has taken measures to resist this attack by requiring Type II cement in the concrete. TxDOT is also taking steps to provide concrete that resists other forces of deterioration.

High performance concrete (HPC) can go a long way in addressing concerns about providing more durable and longer lasting concrete as well as meeting strength and other performance-related criteria. To call concrete high performance implies that it is specialized. In some instances—such as when concrete can obtain high early strength, obtain high final strength, be placed under water without segregating, or self-consolidate without the use of mechanical vibrators—concrete is specialized to meet requirements of a particular application. Specifications to obtain such types of concrete can be made performance-based by requiring certain minimum performance measures, such as strength, slump, and air content, that can be readily tested. However, when HPC is specified to address durability concerns, methods of testing and verification are not as direct. The durability of concrete is discovered over time. Tests can indicate how concrete may perform over time, but typically they take a long time to conduct, and some of the results may not hold up under scrutiny. Therefore, engineers should rely on the latest technologies, the best information available at the time, and good engineering judgment to craft specifications that will provide concrete that will meet the needs of the transportation community. TxDOT has used HPC in a variety of ways and is continually making progress toward the best ways to obtain it.

FIRST USES OF HPC IN TEXAS

During the late 1980’s and early 1990’s, the US Congress authorized a five-year research initiative to develop and evaluate technologies to combat the deterioration of the nation’s highways and to improve their performance, durability, safety, and efficiency. This Strategic Highway Research Program (SHRP) recommended that the Federal Highway Administration (FHWA) initiate a program to implement the use of HPC in bridges, and Texas was one of the states chosen to participate in the program. TxDOT chose two locations to incorporate the HPC technologies:

- The Louetta Road Overpass on State Highway 249 northwest of Houston, completed in 1994, consists of two three-span parallel bridges. HPC was used in the decks, the precast concrete Texas U-beams, and the precast post-tensioned substructures.
- Two bridges were constructed on US 67 over the North Concho River near San Angelo. HPC was used in the deck, the AASHTO Type IV bridge girders, and the substructure of the 8-span eastbound bridge, and in the deck of spans 1 through 5 of the 9-span westbound bridge. *(1)*

Concurrently with the construction of these bridges, TxDOT sponsored a research project by the Center of Transportation Research (CTR) at the University of Texas at Austin to study performance, durability, and effectiveness of the concrete used in these structures. Table 1 provides highlights of the two bridge projects. *(2)*

In addition to the high strengths attained by the concrete in these bridge structures, TxDOT expects the concrete to be more durable than the concrete normally used. The higher strengths specified for the concrete required that a lower water-to-cementitious-material (w/cm) ratio be used, which in turn results in lower concrete permeability. Fly ash was also included in the concrete as a replacement for a portion of the cement. *(2)* Fly ash improves the properties of hardened concrete because of the pozzolanic reaction that takes place. That is, fly ash reacts with free lime, or calcium hydroxide, generated by cement hydration to form more calcium silicate hydrate, or glue (binder), in the paste. The permeability of the concrete was tested in accordance with AASHTO T 277, “Standard Method of Test for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration.” This test is also known as the rapid chloride permeability test (RCPT). All HPC cast-in-place concrete used on these projects had permeability less than 2000 coulombs, which is considered low or very low chloride penetration according to this test and also correlates to FHWA HPC performance grade of 2. *(3)* The RCPT is an indicator test that predicts how well the concrete will perform in keeping water and chlorides from penetrating the concrete and reaching the reinforcing steel. Thus, the performance of this concrete is expected to extend the time before the reinforcing steel begins to corrode and, therefore, increase the life of the structure.

These two bridge projects focused on using HPC for high strength as well as for improved durability. The span lengths, beam spacings, and thickness of the decks were optimized to take advantage of the higher strengths attainable using HPC. From these two projects TxDOT learned the following: *(4)*

- High strength concrete is attainable using local materials.
- Longer spans reduce the amount of substructure needed but necessitate larger capacity hauling systems and cranes, adding concerns about transporting the beams to the job site and about stability of long slender beams, and requiring the beam fabricator to modify or construct new prestressing beds to handle the increased prestressing force.
- The use of high strength concrete allows wider beam spacing.
- Specifying higher strengths for bridge deck concrete in order to increase durability is not effective. The higher strengths require a significant change in the typical construction practice: high-range water reducers are often required to produce concrete with a w/cm ratio below 0.4, which makes concrete placement and finishing more difficult in Texas' typically hot, dry, and windy conditions.

DURABILITY: THE MAJOR BENEFIT

The first uses of HPC in Texas demonstrated that concrete can be designed to possess a variety of properties. One of the least spectacular though significant properties is resistance to deterioration. Durability of concrete structures was likely a selling point of the concrete industry when concrete was being compared to steel. Concrete doesn't need to be painted, and the high alkalinity of the concrete actually protects the reinforcing steel from corrosion. Time has shown that the concrete sales pitch has worked, for in Texas nine out of ten bridges constructed are concrete. Time has also shown that concrete is durable although not always to the extent advertised.

Portland Cement, invented by Joseph Aspdin in 1824, is arguably one of the most significant inventions to affect the construction industry in the past 200 years. Contract plans from bridges constructed in the early 1900's often included the recipe for concrete in the notes next to the structure details. The recipe consisted of Portland Cement, sand, and rock in a 1-2-3 combination, with enough water to make the mix workable. This simple recipe produced concrete for structures that are still functioning adequately today. It is not uncommon in Texas to see bridges that have remained in service 70 or more years. However, much younger bridges are showing signs of significant deterioration. One explanation for why some older concrete seems to perform better than some of the newer concrete is that materials and construction methods are not as good as they used to be. If this explanation is true, it is time to start including other materials in concrete that will make it as good or better than the concrete produced in the distant past.

The Materials: Use of Supplementary Cementitious Materials

Pozzolans such as fly ash, silica fume, and ground granulated blast furnace slag (GGBFS) have been shown to benefit concrete when combined with Portland cement. TxDOT has allowed these supplementary cementitious materials (SCM) in concrete for about fifteen years. In most cases, the use of SCM has been optional for the contractor. Fly ash has been the predominant SCM used as a partial replacement to cement at a rate of 15 to 30 percent. GGBFS has also been used in the western region of the state. The use of GGBFS was initiated by the contracting community, but it is now allowed in all structural concrete at a rate of 50 percent cement replacement. GGBFS is used for cement replacement primarily because it increases resistance to alkali-silica aggregate reactivity (ASR) attack. The aggregates in the western region of the state are highly reactive, and the slag helps mitigate ASR. GGBFS has also helped reduce the heat of hydration and improve the workability of the concrete in this hot and dry environment. The use of silica fume is also allowed, but its use has been limited and not promoted for bridge decks because of finishability concerns.

The Hypothesis: Performance versus Prescriptive Specifications

For the early HPC bridge projects, TxDOT did not specify how the contractor was to obtain durable high performance concrete other than requiring adherence to the *Standard Specifications (5)* accompanying all projects. Contractors were alerted that these bridge projects were part of a research program and that concrete mix designs would be developed by TxDOT and the researchers to meet strength requirements and durability guidelines. A by-product of this research program was an HPC specification to be used on future projects requiring HPC. The specification required that mix designs be formulated and verified to meet strength and permeability requirements before work started. This type of specification relies on the contractor's knowledge and experience to supply concrete to meet the contract requirements. After several projects, it became apparent that the contractors, the concrete suppliers, and TxDOT lacked experience necessary to efficiently design concrete that would meet performance-based specification requirements for durability.

In order to gain experience and better understand the role that concrete constituents have on the permeability results, TxDOT began and continues to use prescriptive specifications that require the use of SCM at a prescribed rate. Concrete specimens are sent to a central laboratory for testing. The contracting community has expressed minimal opposition to the use of prescriptive HPC specifications even though some of the projects require the use of SCM in regions where they have never been used before.

The Test: Actual Bridge Work

Several contracts awarded in the past two years have included HPC specifications requiring SCM in the concrete. Texas' HPC specification is a special provision to the *Standard Specifications (5)* that identifies other requirements for hydraulic cement concrete. The standard specification allows but does not require use of fly ash, silica fume, and GGBFS as partial replacement for cement. As it happens, many concrete suppliers have been using fly ash as a partial replacement for cement because the state has significant quantities of this material and fly ash costs one-third as much as cement. However, not all regions of the state are taking advantage of this material, and most areas are not maximizing the use of it.

TxDOT is aware of concerns about prescriptively specifying the use of SCM when the materials supplier and the contractor are not experienced with the materials, specifically with how the inclusion of SCM affects the strength gain of the concrete. To address these concerns, TxDOT HPC specifications require the contractor to develop time-versus-strength curves for the concrete at 4, 7, 28, and 56 days. Inclusion of fly ash and GGBFS can slow strength gain, especially in cooler weather, and having the contractor plot this curve facilitates synchronization of the concrete mix with the construction schedule. For verification of durability parameters, additional concrete test specimens will be supplied to the central laboratory for the following tests: chloride ion penetrability (AASHTO T 277), freeze-thaw (AASHTO T 161), scaling (ASTM C 672), and abrasion (ASTM C 944). At this time, no results are available for freeze-thaw, scaling, and abrasion tests.

The moist-curing requirements for AASHTO T 277 have been modified from 28 days at 73º F to 56 days at 73º F. This modification allows for the hydration process to progress in mixes incorporating SCM and results in better repeatability of test results. TxDOT is also investigating modification of this curing requirement to 7 days at 73º F and 21 days at 100º F to expedite test results. The higher temperature curing has been shown to produce chloride ion penetrability results similar to specimens cured for 6 month. *(6)*

Lubbock District

Residing in the lower portion of the Texas panhandle, the Lubbock District is in an arid environment with less than 20 inches of annual precipitation, but it is one of colder areas of the state, with temperature swings that cause approximately 70 freezing and thawing cycles annually. The city of Lubbock has a comprehensive highway system, with an Interstate highway and three major state highways going through it. A loop also encircles the city, creating the need for many grade-separation structures to keep traffic moving. The majority of bridges around the city have been constructed in the past 40 years. Many of these bridges are experiencing significant concrete deterioration as a result of reinforcing steel corrosion caused by the application of deicing salts to keep the roads open during snow and ice events. This district is one of the areas where use of fly ash in concrete has not occurred until the past few years.

Just north of the city of Lubbock, two bridges constructed in 1967 were showing signs of significant reinforcing steel corrosion damage to both the superstructure and the substructure. Tests performed on the concrete indicated that the chloride concentration at the level of the reinforcing steel was high. Based on the degree of corrosion damage to the structure and need for additional clearance at this location, TxDOT chose to replace these bridges with thinner prestressed concrete box-beam bridges.

HPC was specified for the substructure concrete and the deck concrete for increased durability. The substructure concrete was designated as Class C (HPC) concrete. Ordinarily, Class C concrete has a minimum specified compressive strength at 28 days (f′c) of 3,600 psi and a maximum w/cm ratio of 0.53. The HPC provision required 4 percent of the cement be replaced with silica fume and 26 percent of the cement replaced by Class F fly ash with a maximum w/cm ratio of 0.47. It also required air entrainment of 5 to 8 percent. This concrete is expected to be resistant to chloride intrusion as well as highly resistant to sulfate attack. In this region of the state, all concrete exposed to the ground is required to be resistant to sulfate attack. Testing performed to measure resistance to chloride ion penetration using the RCPT showed that this concrete had an FHWA HPC performance grade of 3, which means the results were less than 800 coulombs. The average of the actual values was 676 coulombs.

The concrete used in the bridge deck and the box beam shear keys was designated as Class S (HPC) concrete. Class S concrete normally has a minimum f'c of 4,000 psi with a maximum w/cm ratio of 0.44. The HPC provision required 30 percent of the cement be replaced with Class F fly ash. It also required air entrainment of 5 to 8 percent. Because of concern about the possibility of not attaining the 4,000 psi compressive strength at 28 days due to slower strength gain as a result of the use of Class F fly ash in cold weather, the 28-day strength was lowered to 3,000 psi and an additional requirement of 4,000 psi at 56 days was added to the plans. In terms of structural design, 3,000 psi is sufficient to resist the forces created by loading this type of structure, but 4,000 psi for deck concrete is required to meet FHWA requirements. The RCPT performed on this concrete showed it to have a performance grade of 2, which means the results were between 800 and 2,000 coulombs. The average of the actual values was 1,057 coulombs. RCP testing was also performed on concrete that had previously been used in this district that did not contain fly ash. The average of the actual values was 3,926 coulombs. Thus, the improved resistance to chloride ion penetration is dramatic. The mix design information for the Class C (HPC) and the Class S (HPC) with and without fly ash is shown in Table 2.

Corpus Christi District

The Corpus Christi District is in south Texas, and it borders the coastline of the Gulf of Mexico. TxDOT advocates the use of HPC in this district to combat the damage caused by chloride-induced corrosion attributed to the coastal environment. In December 2001, TxDOT awarded a contract to raise Park Road 22, the only road connecting Corpus Christi to North Padre Island. The change of elevation was to be substantially accomplished using prestressed concrete sheet piling and fill. However, a portion of the raised section consisted of a 2,850-foot long bridge inserted to supply an additional opening that would improve water circulation into the bay from the intracoastal waterway. This bridge is comprised of prestressed concrete AASHTO Type IV beams spans supported on trestle-pile bents, consisting of 24-inch prestressed concrete piling and a reinforced concrete bent cap. The structure is designed to resist 120-mph winds as well as tidal forces that may be associated with a hurricane. The structure is designed to be robust, and its materials must complement this design.

HPC was specified for the prestressed concrete piling, the cast-in-place bent caps, and the deck concrete for increased durability. Specifications required that 25 percent of the cement be replaced with Class F fly ash for Class C (HPC) concrete used in the cast-in-place bent caps and Class S (HPC) concrete used in the bridge deck. This requirement provides concrete with reduced permeability and increased resistance to sulfate attack. Additionally, TxDOT requires use of Type II cement in concrete for structures in the Gulf of Mexico coastal environment. This project also used standard Class C concrete in members not directly exposed to the salt spray conditions, providing an opportunity to compare the two concretes using the RCPT. The results show a value of 1,243 coulombs for the standard Class C concrete and a value of 750 coulombs for the Class C HPC. These results were obtained from specimens cured for 16 days at 73º F and for 21 days at 100º F. See Table 3 for design mix information. The mix design for the Class S HPC has not yet been developed.

The prestressed concrete piling for this project was specified to be fabricated with Class H (HPC) concrete with a minimum compressive strength at release of the prestressing of 4,000 psi and a minimum 28-day compressive strength (f'c) of 5,000 psi. The maximum w/cm ratio of this concrete is 0.49. The specifications required that the concrete mix contain silica fume and Class F fly ash at a 5 percent and 19 percent replacement of the cement.

Initial mix designs—Class H (HPC) #1 and Class H (HPC) # 2—did not provide the early release strength that the fabricator needed to maximize the use of the stressing beds. The relatively slow-acting Type II cement combined with an insufficient amount of cement to react initially with the pozzolans may have contributed to this problem. The amount of cement was increased for mix design #3, Class H (HPC) #3, and has consistently obtained release strengths in 17 hours. The average RCPT results for mix design #1 are 317 coulombs. The test results for mix designs #2 and #3 are not available at this time. See Table 4 for mix design information.

In the future, use of Type III cement and a ternary blend of SCM will be considered when early strength and sulfate resistance is desired. *(7)*

Other Uses

In other situations TxDOT has taken advantage of some of the beneficial aspects of HPC. One unexpected use of high performance concrete technology occurred this past year. The only bridge that connects the Texas mainland with South Padre Island was taken out of service as a result of an errant barge colliding with the bridge piers. Five spans had to be reconstructed for the bridge to be reopened. The economic impact to the island community was significant each day the bridge was closed. TxDOT's experience on earlier HPC projects with the use of high range water reducers to reduce the w/cm ratio provided guidance for both TxDOT and the contractor and resulted in expediting the reconstruction of the bridge in 52 days from the start of construction.

A contract was recently awarded to replace reinforced concrete box culverts on a road in an oil-rich area of the state. The existing box culverts have deteriorated as a result of reinforcing steel corrosion. The soils are contaminated with salt in this particular area as a result of past oil drilling exploration. Provisions for this project included prescriptive specifications and performance-based specifications. Prescriptive HPC specifications requiring the use of silica fume and fly ash were used for all cast-in-place concrete. Performance-based HPC specifications for the fabrication of the precast concrete box culverts require that the contractor design and verify that the mix design meets a RCPT value below 1,000 coulombs. Fabrication of precast culverts requires use of concrete that typically has a low slump and is placed with either a slip-forming method or spun-concrete method. The low w/cm ratio of this concrete may result in permeabilities that achieve the RCPT requirements using the fabricator's standard mix without additional SCM.

TxDOT also understands the benefits SCM provide in the production of ASR-resistant concrete. The current specifications allow the contractor the option to include SCM at prescribed amounts in all structural concrete, to use a lithium nitrate admixture, or to restrict the total alkali content of Portland cement concrete.

FUTURE DIRECTION

TxDOT expects its promotion of HPC to have a long-term positive effect on the quality of structures in the state. Research started on the first HPC structures constructed in the 1990's continues, and the findings reveal no significant concern about performance thus far. Long-term monitoring of the bridges constructed using increased durability HPC is being conducted to ensure that TxDOT is achieving more durable, longer lasting structures. TxDOT continues to test the concrete for performance-related criteria that can eventually be correlated with actual field conditions of the bridges.

The use of fly ash, silica fume, and GGBFS in Texas is increasing, and bridge designers and contractors are seeing the benefits of using these materials. TxDOT is continuing to examine methods to specify the use of HPC. As contractors gain experience providing concrete that meets prescriptive specification requirements, TxDOT will move toward performance-based specifications.

REFERENCES

1. Ralls, M.L., "Texas HPC Bridge Decks", ACI *Concrete International*, V. 21, No. 2, Farmington Hills, MI, 1996, pp. 63-65.
2. Ralls, M.L., R. L. Carrasquillo, and N. H. Burns, "Optimization of Structural Design for High Performance Concrete Bridges," *Transportation Research Record*, No. 1624, 1998, pp. 132-139.
3. Goodspeed, C. H., Vanikar S., and Raymond, A. C., "High-Performance Concrete Defined for Highway Structures," ACI *Concrete International*, Vol. 18, No. 2, Farmington Hills, MI, 1996, pp. 62-67.
4. Ralls, M.L., "Louetta Road Overpass-Lessons Learned", *HPC Bridge Views*, Issue No. 1, www.portcement.org/br/newsletters.asp.
5. Texas Department of Transportation, *Standard Specifications for Construction of Highways, Streets, and Bridges*, 1993 edition.
6. Ozyildirim, C. "Permeability Specifications for High-Performance Concrete Decks," TRR 1610, Concrete in Construction, TRB, National Research Council, Washington, DC, 1998, pp. 1-5.
7. ACI Committee 201, "Guide to Durable Concrete," ACI 201.2R-01, *ACI Manual of Concrete Practice*, Part 1. American Concrete Institute, Detroit, 2001.

LIST OF TABLES

TABLE 1 Geometry and Strength Summary.

	Louetta		San Angelo	
Maximum Values	**Northbound**	**Southbound**	**Eastbound**	**Westbound**
Span length, ft.	136.5	134.0	157.0	140.3
Beam spacing, ft.	12.94	16.62	11	8.26
Beam f′c, psi (Dsn/Act)	13,100/14,440	13,100/14,550	14,000/15,240	8,900/10,130
Deck thickness, in.	7.25	7.25	7.5	7.5
Deck f′c, psi	4,000/5,700	8,000/9,100	6,000/7,345	4,000/6,120

TABLE 2 Mix Design Information for Lubbock Concrete.

Mix Constituents (lbs/yd)	Class C (HPC)	Class S (HPC) 30% FA	Class S w/o FA
Cement Type I/II	367	397	588
Fly Ash (Class F)	137	181	-
Silica Fume	25	-	-
Coarse Aggregate	1,854	1,854	1,960
Fine Aggregate	1,241	1,174	1,133
Water	250	260	260
W/cm	0.47	0.45	0.44
Permeability (AASHTO T 277)	676 coulombs	1,057 coulombs	3,962 coulombs

TABLE 3 Mix Design Information and Test Results for Corpus Christi Class C Concrete.

Mix Constituents (lbs/yd)	**Class C (Standard) 17% FA**	**Class C (HPC) 25% FA**
Cement Type II	451	395
Fly Ash (Class F)	84	128
Coarse Aggregate	1,850	1,900
Fine Aggregate	1,204	1,158
Water	186	188
W/cm	0.35	0.36
Permeability (AASHTO T 277)	1,243 coulombs	750 coulombs

TABLE 4 Mix Design Information and Test Results for Corpus Christi Class H (HPC) Concrete.

Mix Constituents (lbs/yd)	**Class H (HPC) #1**	**Class H (HPC) #2**	**Class H (HPC) #3**
Cement Type I/II	488	540	586
Fly Ash (Class F)	137	149	161
Silica Fume	42	42	49
Coarse Aggregate	1,872	1,872	1,869
Fine Aggregate	1,231	1,122	981
Water	228	248	271
W/cm	0.34	0.34	0.34
fc @ 17-19 hours	3,000 psi	3,790 psi	4,760 psi
fc @ 7 days	6,330 psi	6,500 psi	7,340 psi
f’c @ 28 days	8,320 psi	8,690 psi	9,138 psi
Permeability (AASHTO T 277)	317 coulombs	N/A	N/A